5-2016

Efficiency and Particulate Matter Emissions Testing of Wood Burning Heating Units

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I participated in the WERC design competition with a team of six members. While the project was a thorough group effort, there were many individual contributions. From the beginning phases I was involved in the initial experimental design and procedure writing. This led to my involvement in the construction of the first and second testing apparatus. And finally I worked to get the stove moved to New Mexico to be displayed for the competition.

Working with another member of the team, we designed a testing apparatus that controlled the smoke exhaust from a wood burning stove. This design also required a fan and manometer to regulate the draft on the stove. Because we were placing a heat exchanger in the pipe, this created a large pressure drop and would adversely affect the burning capabilities of the stove. To counteract this a variable speed fan was to be placed in line directly downstream from the heat exchanger, and controlled to maintain the slight vacuum produced in the stove due to burning. This would allow the team to cool the stack gas to a temperature so that safe volumetric flow measurements could be taken of relatively cool gas.

I also took the lead in constructing the testing apparatus for the Hog Method. The heat exchanger was composed of a car radiator encased in a sealed concrete board box. The concrete board had to be cut using methods to prevent large amounts of dust from being inhaled, which involved special tools. Once the box was constructed, several modifications were made to the radiator to allow it to fit tightly in the box, and the edges were sealed with high temperature silicone to ensure all the smoke flowed through the radiator. A water recirculation system was also needed in conjunction with the radiator. The original design utilized a five gallon bucket and a submersible pump, but after experimenting with the design we found that the reservoir temperature heated quickly, and the submersible pump seized at around 160^{o} F. To fix this I worked with an advisor to get a new pump that could handle heat, and a larger reservoir. With this modified system we were successfully able to cool the smoke stream through the duration of the entire test, allowing the collection of data required for analysis.

I also led the construction of the efficiency sampling train which diluted smoke with air to concentrations measureable by our carbon dioxide and carbon monoxide meters. This involved testing the system and installing all equipment on a portable apparatus. I also worked to test the scales to be used to weigh the stove, and when the original scales failed to satisfy the needs of the project I helped select the new scales and calibrate them.

Throughout the first round of testing, I collected and split wood to create the pre-test and test charges. This involved splitting the bark off of oak cordwood and weighing the charges. I was also involved with running the first tests, including operating the stove and heat exchanger during the test, and assisting in data collection. I also wrote the procedure for constructing the testing apparatus, and the experimental procedure.

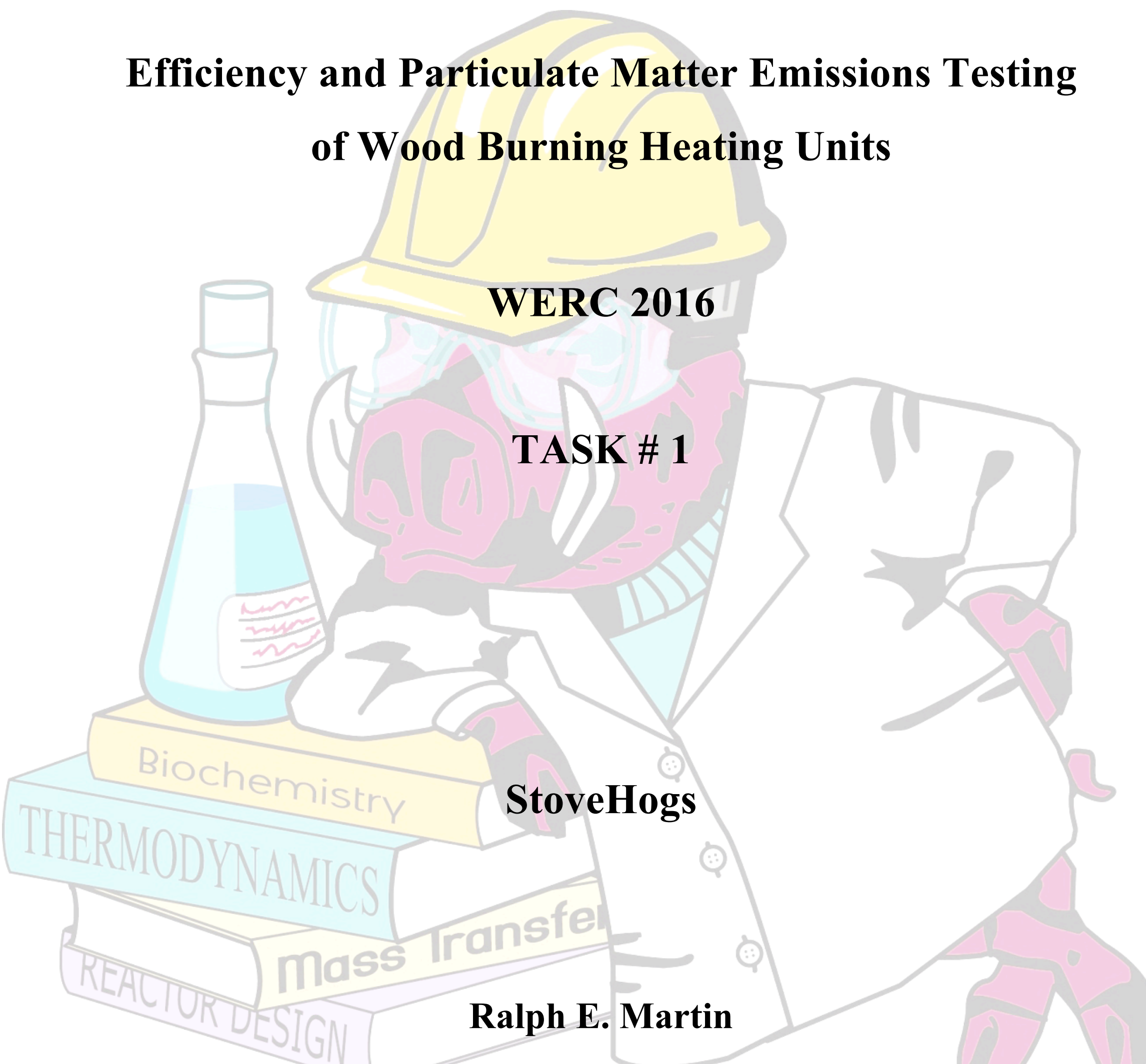
After the first round of testing, the data was analyzed and the group worked together to determine a new Optimal Hog Method. This method required some redesign work in which I rearranged the dilution system and added a water trap. These changes resulted in alterations to the procedures, to which I made the necessary modifications. This also led to a second round of testing where I collected data and ran about half of the tests.

I also contributed to the paper through the first draft of the experimental apparatus and optimal apparatus sections. I also worked to proofread and edit the later versions of the report, and I wrote the background and Optimal Hog Method description sections of the poster as well.

My role in the project also including determining a method to move the nearly 1000 pound stove to New Mexico. To do this an engine hoist was tested and proved to not be plausible. Instead a shop hoist was used to load the stove and the stove was partially dismantled in New Mexico so that it could be lifted out of the truck by hand. Luckily a forklift was located to reload the stove for the trip home.

Appendix

Efficiency and Particulate Matter Emissions Testing of Wood Burning Heating Units



WERC 2016

TASK # 1

StoveHogs

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Efficiency and Particulate Matter Emissions Testing of Wood Burning Heating Units

Task # 1 – Open Category

StoveHogs

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EXECUTIVE SUMMARY

The environmental impact of wood burning for residential heating is an issue of national importance. The 2000 census determined that approximately 1.7% of households rely on wood burning as their primary heat source, and the demand is growing – in 2010 the number increased to 2.1%, showing an rise of 34%, which represents the fastest growth rate among fuels used for heating.[22] In twelve different states, more than 3% of the population relied on wood for heating in 2000, and a 90% surge in wood usage was seen in eight of those states in the year 2010. There are two main reasons for the growing dependence on wood for heating purposes. The first of these is locational: some households do not have access cheap sources of electricity or natural gas. Homes in rural areas find it convenient to use natural resources such as wood to heat their homes.[6] Heating fuel choice tends to vary depending on location and readily available resources. A second factor is economic: historically, low- and middle-income households have been more likely to use wood as a primary heating source.[6] These households rely on wood burning to alleviate the cost associated with the purchase of natural gas.

The Environmental Protection Agency (EPA) has had regulatory control of the wood burning stove industry since 1988.[6] There are certain standards associated with particulate matter (PM) emissions that each stove must meet before being introduced to the market as a potential source of residential heating. The EPA Methods are used in conjunction with criteria set forth by the Canadian Standards Association (CSA) to create standards for stove operation during testing. In order to be EPA certified, each stove design must be tested and proved to meet these standards (both EPA and CSA) by an EPA certified testing laboratory. The cost of a certification test is quoted to fall in the range of \$10,000 – \$12,000.[8,13,25] This estimate does not include shipping costs, research costs to find the optimal burn rates, or consultation costs if the stove fails. It is not uncommon for a newly designed stove to spend 6 – 12 months in the research and development (R&D) stages, often running up a bill in the \$100,000 – \$150,000 range.[11] This price tag is a significant economic barrier for backyard inventors or small manufacturers who feel they have a novel design that may burn more cleanly and efficiently than competing stoves from larger manufacturers.[8] Larger manufacturers seem to be unfazed by this monetary hurdle.

Regulating the PM emissions from wood burning stoves is important from both a health and environmental standpoint. Particulate matter that is less than 2.5 µm in diameter ($PM_{2.5}$) is harmful to human lungs, and contributes to the fouling of the atmosphere.[18] The newest EPA regulations for residential wood heaters, hydronic heaters and forced air furnaces have the ability to reduce the $PM_{2.5}$ emissions in the United States by 8,269 tons per year.[18] Starting in 2015, 46,000 tons of carbon monoxide emissions will be avoided, as well as 9,300 tons of volatile organic compounds.[18] The EPA estimates that as a direct result of their final ruling 810 premature deaths per year related to harmful substances in the environment will be eradicated.[18]

Many small manufacturers do not have the resources or the knowledge to determine whether or not a newly designed stove will produce PM emissions that are below the legal limit as stated by the EPA.[11] By removing – or at the very least reducing – the economic barrier for small manufacturers and backyard inventors of wood stoves, competition in the stove industry would increase. This intense shift in focus would benefit the consumer wishing to obtain the maximum benefit possible from their wood-burning stove. Reducing the economic barrier associated with bringing new stoves to market will result in a more competitive business environment that will lead to more efficient, less environmentally impactful, and reasonably priced designs of wood stoves. The Hog Method is designed for simplicity and ease of use. It has the potential to assist with reducing the economic barrier faced by companies and individuals, while providing insight into the complexity that exists within the industry.

INTRODUCTION

Wood burning was brought to the attention of the StoveHog team through a stove design that loads from outside the building. This rear loading feature eliminates the need for wood to be brought inside, and prevents smoke from entering the room during loading. The initial design was intended to service a 5,000 square foot shop, with an ultimate goal of building a smaller unit for residential applications. This initial design was built much larger than residential wood stoves that are currently on the market. The firebox volume of the designed stove compared to residential wood stoves is 11.6 cubic feet (ft^3) to 0.5-4 ft^3 respectively.[23] After designing the stove, the owner wanted to determine the efficiency and possibility of selling the stove. The StoveHog team took on the task of exploring the requirements for efficiency calculation and EPA certification. Four different regulations were researched that specify requirements for testing wood burning stoves: EPA Method 5G(Determination of Particulate Matter Emissions From Wood Heaters (Dilution Tunnel)), EPA Method 5(Determination of Particulate Matter Emissions from Stationary Sources), EPA Method 28(Certification and Auditing of Wood Stoves) and the CSA B415.1-10.[16,15,14,3] The complexity of the regulations on wood burning, expense of testing at an EPA approved facility, and lack of available information on efficiency calculation led to the creation of the Hog Method.

The team's focus of the StoveHog team was to identify a manner in which to lessen the economic burden on both backyard inventors and smaller manufacturers of wood stoves by designing a test apparatus to evaluate both efficiency and PM. Simply stated, The Hog Method testing apparatus is less complex and less expensive than the current options for efficiency and PM emissions testing. The EPA does not demand that stoves obtain a certain overall efficiency.[14] However, the higher the efficiency of the stove, the less wood is needed to maintain heating, the greater the economic benefit to the consumer, and the more attractive the wood stove becomes as a source for residential heating. While it is the general consensus that carbon monoxide (CO) and PM correlate, this assumption leaves much to be desired in determining the actual PM emissions produced from a wood burn.[8,13] Therefore, methods that focus solely on manipulating the ratio of CO to carbon dioxide (CO_2) in the flue gas function well to inform design changes, but cannot conclusively determine the rate of PM emissions in grams per hour (g/hr) as requested by the EPA.[8] The StoveHogs concluded that the best way to sample both the PM emissions and calculate the efficiency of the stove was to design a method and construct an apparatus that could be used in conjunction with the normal installation and operation of a stove.

The tradeoff between environmental preservation and economic gain is not new. For centuries humanity has traded environmental exploitation for economic gain. While burning wood cannot be proven as the most environmentally friendly option for heating, it is a sustainable option, it will not fall into disuse soon, and it has the potential to reduce the United States' dependence on imported fossil fuels.[7] Because there exists a niche market in which wood burning will remain – and perhaps grow as – a primary residential heating source, it is important to foster a competitive market in which constant design improvements are encouraged.[22] In order for the industry to remain relevant, competition and continued production of improved stoves is essential.

DESIGN THEORY

The majority of the design for the testing apparatus was driven by the standards presented by the EPA and by the CSA. After analyzing the procedure and requirements presented in these documents, the Hog Method was created to mimic the emissions certification and efficiency determination tests performed by the EPA certified testing facilities. The creation of the Hog

Method led to the design and construction of a testing apparatus "in-shop" that would give informative results. The creation of the Hog Method led to the design of the testing apparatus discussed in the Experimental Apparatus section of this report. The results obtained from the apparatus are presented in the Experimentation and Results section of this report.

EPA Standards

The main goal of the EPA testing method is to operate a stove at four standardized burn rates, and monitor the stove's particulate emissions at each of these burn rates. The EPA documents that proved most useful to designing the testing apparatus were Method 28, Method 5G, and Method 5.[14,16,15] Method 28 influenced the construction decisions regarding the efficiency sampling train, while Method 5G and Method 5 proved useful in determining particulate emissions. These EPA methods are complex, costly, require high precision, and are difficult to replicate on a small budget.[9,13] Because the stove tested was much larger than the average certified non-catalytic stove, the team was forced to make a few important changes.[24] One variation from Method 28 is the removal and replacement of the dilution system. The Hog Method focuses on cooling the flue gas in-line, and then uses this cooled flue gas for composition sampling and volumetric flow measurement. The size of the stove made it difficult to create a sustained burn at the four standardized burn rates prescribed by Method 28.[14] The EPA's method for determining the burn rate categories is driven by specified numerical values.[14] The Hog Method team opted to focus on only two burn rates due to time constraints: a max burn rate at 100% primary air (all primary air openings unblocked), and a second burn rate at 50% primary air (half of primary air openings unblocked). These burn rates are more reminiscent of the burn categories used in the CSA.[3] The Hog Method used oak cordwood in place of the EPA specified douglas fir dimensionalized wood to anticipate a future ruling from the EPA that will switch from dimensionalized wood to cordwood.[8,14] Oak was a more readily available wood in northwest Arkansas where the stove was operated during testing. Using cordwood allows the particulate results to reflect a more realistic effect of everyday wood burning on the environment. The sizes and ratios of pre-test fuel charge and test fuel charge to the volume of the firebox proved to produce a desirable burn in the stove according to the Hog Method, and so were carried over from the EPA standards.[14] In the Hog Method, two pre-test fuel charges are burned to obtain a more even heating profile throughout the stove box.[11] The main variation from Methods 5 and 5G is the absence of water vapor condensers in the particulate emissions line.[15,16]

The Hog Method also approves deionized (DI) water as the primary cleaning solution for the particulate emissions sampling train between runs. Acetone may be used in the case of excessive particulate accumulation, but the decision is left to the administrator of the test.[15] The Hog Method utilizes DI water because it is accessible to a larger group of people and can be evaporated safely without the use of a fume hood.

Canadian Standard Association

The CSA Standard B415.1-10 analyzed results regarding testing for stove efficiencies.[3] B415.1-10 is essentially identical to EPA Method 28, but with the added benefit of providing a user-friendly Excel program for data reduction.[8,13,25] The Excel program presented in B415.1-10 is widely used in testing facilities and manufacturing facilities for the determination of stove efficiencies. Overall, industry professionals are pleased with how the program functions and encourage its use for stove testing. The Excel data reduction program that accompanies B415.1-10 was examined carefully to determine if the written program was useful for the needed calculations of the Hog Method. Though satisfactory documentation of the program is not provided with the purchase of the standard, the StoveHogs were able to verify the legitimacy and accuracy of the program through a personal interview with the author, Rick Curkeet. Mr. Curkeet is the chief engineer at Intertek Testing Services, and was able to acceptably answer all the questions related to the theory and calculations of the data reduction program. The program is primarily designed for appliances with high combustion efficiency. Therefore, in cases where the combustion efficiency is below 85% or where the O_2 concentration in the flue gas is high, the algorithm of the program is not as accurate in giving results.[5] Though this may present a problem during preliminary testing of non-approved stoves, this data reduction program is the best option to calculate efficiencies and is therefore applied in all scenarios.[5] The Hog Method apparatus design takes into account the necessary inputs for the B415.1-10 Excel program, and equipment was selected to generate data to effectively use the program.

EXPERIMENTAL APPARATUS

The development of the Hog Method experimental design was achieved through the careful consideration of standards set forth by the EPA and the CSA and any consequences that would arise from deviations from these methods. Two sampling trains were assembled to gather information on PM emissions and to generate data for calculating the reported efficiencies.

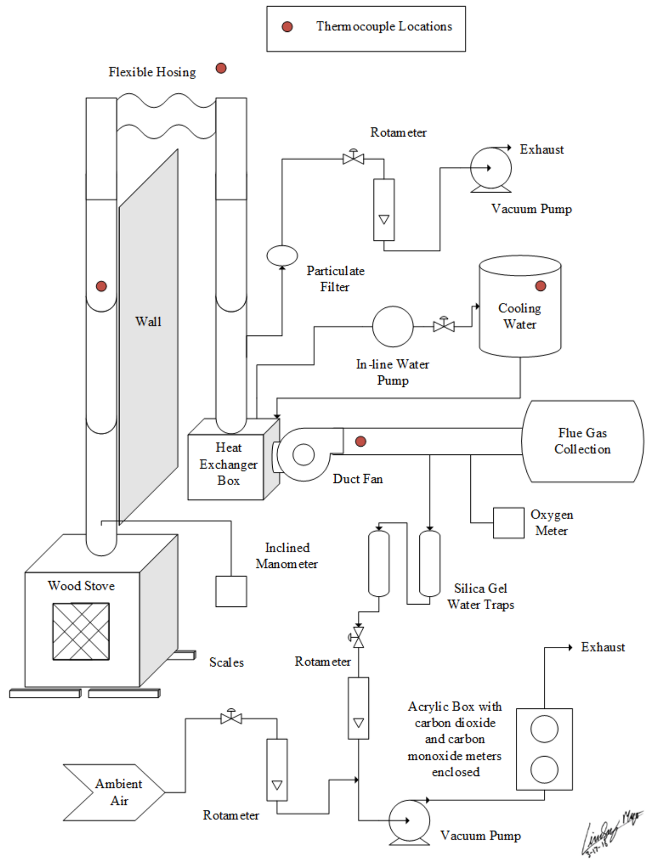

Figure 1: Experimental Apparatus Overview

The unique design of the tested stove required that the stovepipe be installed through the wall of the testing facility at a 12-foot height. Flex hose was used to isolate the weight of the inside portion of the stovepipe and stove in order reduce the variability of the scale readings during test runs. A set of 4 identical shipping scales was individually placed under each of the stove legs to obtain weight measurements.

It was concluded that the best way to sample the flue gas was to design this testing apparatus to function with the existing stove design in normal operation. Additional stovepipe was used to bring the flow of flue gas closer to ground level outside. This stovepipe was supported by an 8-foot folding table at approximately 3 feet above ground level. A second 6-foot folding table was placed next to the 8-foot table to provide support for the two sampling trains and accessories to the heat exchanger. The exiting flue gas vented to atmosphere at the end point of the larger table.

Efficiency Sampling Train

Test charge weight was determined using the calculation set forth in EPA's Method 28.[14] To collect experimental data concerning the efficiency and flue gas properties, a heat exchanger was installed in-line outside the testing facility to cool the flue gas to a temperature of approximately 165°F, to keep the flue gas above its due point and avoid condensing water in the flue gas. Figure 1 provides a schematic of the heat exchanger setup and accessories.

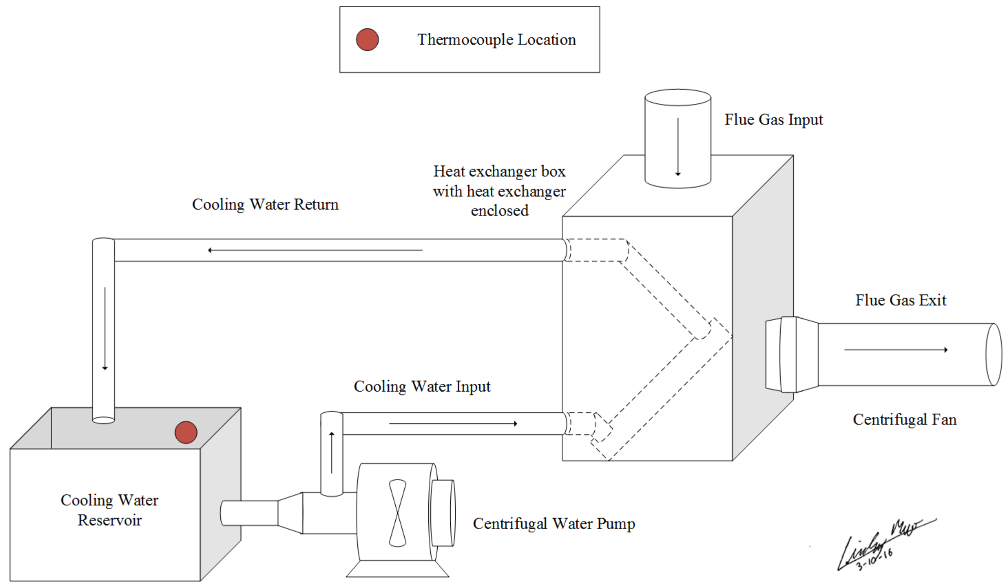

Figure 2: Heat Exchanger Schematic

The heat exchanger was constructed from a car radiator inside a silicone sealed 18 x 24 x 36 inch concrete fiberboard box. The radiator is positioned on its short side in a slanted fashion to allow the flue gas to enter and exit from top to bottom within the box. The flue gas entering the box is first directed away from the radiator using a stovepipe elbow placed inside the box to ensure the gas is well mixed above the radiator before cooling. The car radiator requires continual water flow to cool the passing flue gas. Vinyl tubing, with the radiator inlet tubing attached to a pump, is used to service the radiator with cooling water from a plastic reservoir. All tubing entering and exiting the box as well as the radiator within the box are sealed to the edges of the box with silicone.

A variable speed fan was placed after the heat exchanger, as seen in Figure X above, to mimic the vacuum that is pulled by the draft in the stovepipe created in normal operation. The draft naturally created by the stove is compromised because of the addition of the testing apparatus, and must be reestablished by adjusting the fan speed. An inclined manometer was tapped off the stovepipe immediately above the stove box to monitor the draft.

The primary method of determining the burn rate was using the scale readings over time to determine the pounds per hour (lb_m/hr) weight lost in the stove. A bag collection method that calculated volumetric flow rate required an empty collection bag with volume 7.8ft^3 to be placed on the open end of the stovepipe and inflated for measurements. The time at which the bag is inflated completely was determined by observing a sharp increase in pressure at the exit of the stovepipe, monitored by a homemade manometer. This manometer was easily assembled with a clear, plastic, sealed container housing water and a U-tube. These results are discussed in the Experimentation and Results section of this report.

In conjunction with determining accurate burn rates, the efficiency of the stove requires the measurement of carbon monoxide (CO) and carbon dioxide (CO_2) in the flue gas. The efficiency train schematic constructed to obtain these measurements is presented in Figure X.

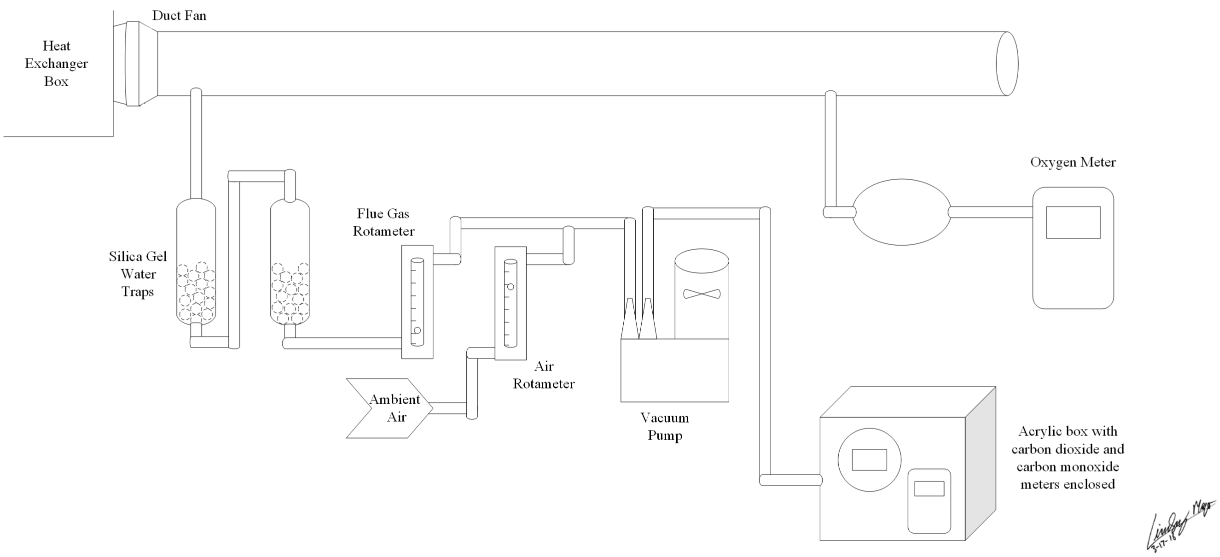

Figure 3: Efficiency Sampling Train for Experimental Apparatus

Two sampling ports were installed following the heat exchanger; one for flue gas to mix with dilution air to bring CO and CO_2 concentrations within the measureable limits of the CO and CO_2 analyzers, and the other to measure percent oxygen (O_2). At the first sampling port, The Hog Method dilution system involved two rotameters in parallel, being pulled by a single vacuum pump with ¼ inch vinyl tubing. Before the dilution system, two silica gel beds were used in series to dry the flue gas sufficiently before being sent through the analyzer box where measurements were taken. The first rotameter was used to control the flow of flue gas from the stovepipe, and the second was used to monitor the flow of ambient air entering the dilution system. The two outlet streams of the rotameters were mixed downstream of the pump using a tee-joint before reaching the CO_2 and CO analyzers. The use of rotameters in the dilution system of the Hog Method controlled the mixing ratio of ambient air to flue gas. The CO_2 and CO analyzers were placed in a silicone sealed, acrylic box with inlet and outlet tubing connections.

The outlet of the box containing the CO_2 and CO analyzers was vented to atmosphere. The second sampling port was installed for the O_2 analyzer to manually take readings directly from the flue gas. This sampling port was located at the end of the stovepipe and manual readings were taken to stoichiometrically check the values of the CO_2 and CO analyzers. After passing through the cooling system, the stovepipe was vented to the atmosphere. Guidelines provided by the EPA for pre-test ignition weight and test charge weight were followed to give controlled variables during the tests.[14] Data on mass and moisture content for the pre-test and test charges were recorded prior to testing.

Particulate Emissions Sampling Train

The goal of the PM emissions sampling train was to accurately determine, given the available equipment, the emissions from the tested stove in units of grams per hour (g/hr). An overall schematic of the particulate emissions sampling train can be seen in Figure 4.

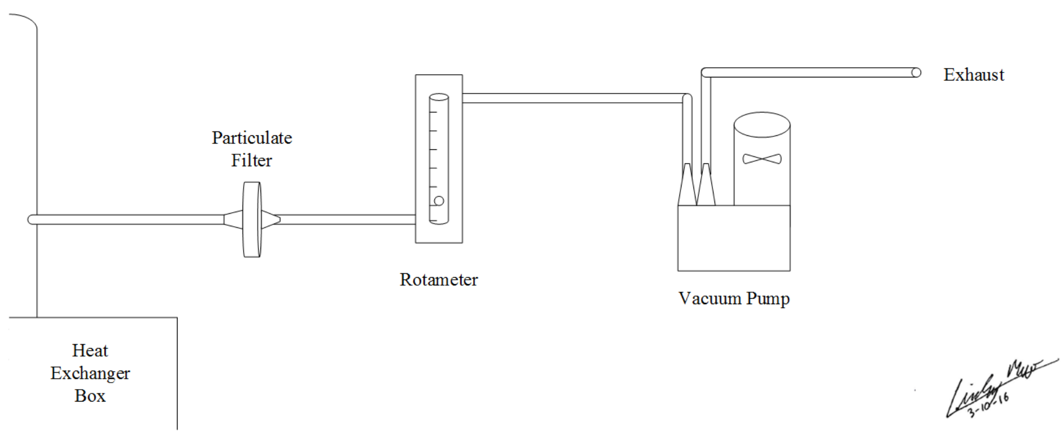

Figure 4: Particulate Emissions Sampling Train

The PM emissions sampling port was located upstream of the in-line heat exchanger to prevent any PM from depositing on extra surfaces before the filter. The stovepipe was tapped with a ⅜ inch silicone tube and fitted with a length of ½ inch silicone tubing to create an airproof seal on the filter holder inlet. Over a tube length of 10 feet, the flue gas cooled to within the temperature tolerance of the subsequent equipment before reaching the filter. The filter and filter holder selected for use by the Hog Method were identical to those recommended by EPA Method 5G.[16] Immediately following the filter, a rotameter was used to control the flow of flue gas through the filter system to obtain an accurate calculation of total particulates collected through the test run. The PM emissions train was pulled by a vacuum pump downstream of the rotameter and was vented to atmosphere. Between each test run, the PM emissions sampling train was cleaned thoroughly with DI water to collect any particulates that may have deposited on the tube surfaces during a burn period and to avoid contamination within the lines from one run to the next.[15]

EXPERIMENTATION AND RESULTS

To evaluate the Hog Method, five total test runs were completed to determine if repeatability of results could be achieved with the Hog Method, and to estimate the total PM emissions and efficiency of the stove using the designed apparatus. The Hog Method of testing is condensed in the numbered procedure below.

1. Zero the scales with the loading door closed.
2. Begin the pre-test by loading the pre-test ignition into the ash-free stove to begin a burn.
3. Set the primary air conditions needed to achieve the desired burn rate during the test run once 50% of the pre-test ignition has burned.
4. Record the weight of the test charge.
5. Zero the scales with the loading door closed once the pre-test ignition has burned to 20-25% of the test charge weight.
6. Load the test charge immediately. This indicates the end of the pre-test and the start of the test run.
7. Take all appropriate measurements needed for efficiency calculations and PM emission determination at an interval no more than 10 minutes.
    a. Adjust rotameters to counteract the vacuum pump pull overtime.
    b. Monitor pump reservoir temperature to keep the fan outlet temperature above the flue gas dew point and within the pump's service temperature.
8. The test run is concluded when the scales indicate zero weight in the stove.

Pre-test ignition and test fuel charges were compiled using oak cordwood at approximately 14% moisture content. Because of the set-up of the apparatus in-line with the stovepipe, measures had to be taken to mimic the natural draft created by normal operation of the stove. Creating draft is an important component in the operation of a wood-burning stove. Draft is caused by differences in air density due to the temperature gradient through the stovepipe, and regulates the burn rate inside the firebox and affects the efficiency of the burn. For this reason it was necessary to conduct test runs at each tested burn rate without the sampling trains installed to understand the draft normally pulled by the stove prior to running full tests. These initial runs were conducted using a manometer tapped into the stovepipe just above the top of the stove. A reading was taken every 5 minutes for up to 2 hours to determine the necessary draft to mimic during full test runs.

For each test it was necessary to record the following data: elapsed time in minutes, the fuel weight remaining, flue gas composition of CO, CO_2, and O_2 in percent, the stack temperature at 8ft, and the temperature of the testing facility. This data was used in conjunction with known properties of wood to calculate the desired information. The overall combustion equation (Equation (1)) for the burning of wood, a compound containing carbon, hydrogen, and oxygen, is central to all of the calculations.

$$wC_aH_bO_c + uO_2 + 3.77uN_2 \rightarrow dCO_2 + eCO + gO_2 + hN_2 + jH_2O + kCH_4 \qquad (1)$$

The data reduction was accomplished through the CSA Excel program, which requires only the percent of CO and CO_2 to calculate the excess air in the reaction.[3] The percent O_2 in the flue gas is determined from the measured CO and CO_2 data, the calculated value of excess air, and the stoichiometric combustion equation (above). Testing inputs provide the values of *d, e,* and *g* for Equation (1), while the fractions of carbon, hydrogen, and oxygen in wood are known from the properties of wood.[9] Using these known values and a mass balance of the combustion equation, all of the other molar amounts of reactants and products are determined. The total input energy into the stove is determined from the weight of the wood and the higher heating value (HHV) of wood. The HHV of oak is 19,887 kJ/kg.[3] The total output energy of the stove is determined by the total energy loss subtracted from the total input. The energy loss rate, or heat content change, of the stove was calculated from the specific heat capacities of each of the products, the temperature difference between the stovepipe and the testing facility, and the moles of the product per kilogram of wood.[3] This energy loss rate was then multiplied by the dry weight change over each interval in order to give the total energy loss, giving the total output energy. The total weight of CO in grams was also calculated from the mass balance of the combustion reaction.

Three different efficiencies are reported in the data reduction program: overall efficiency, combustion efficiency, and heat transfer efficiency.[3] The overall efficiency represents the ratio of heat transferred to ambient air to the total heat available. It is represented in Equation (2) below:

$$Overall\ efficiency = \frac{Total\ output}{Total\ input} \quad (2)$$

The combustion efficiency represents the ratio of the total energy available to the energy actually released. It is a measure of how close the reaction is to complete combustion and is represented in Equation (3). Complete combustion is defined as all of the carbon from the wood reacting during combustion to form CO_2. If CO and CH_4 are present, incomplete combustion has occurred. The chemical loss of energy as a result of CO and CH_4 being present is determined from their higher heating values, 10.1069 and 55.6344, respectively, and the weight of each product produced in grams.[3]

$$Combustion\ efficiency = \frac{Total\ input - sum(chemical\ loss)}{Total\ input} \quad (3)$$

The heat transfer efficiency represents the ratio of heat transferred to ambient air to the heat lost up the stovepipe. It is also described as the percentage of heat energy that is transferred to the space surrounding the stove. In the data reduction program, this value is determined from the ratio of overall efficiency to combustion efficiency as shown in Equation (4). This can be done because overall efficiency is calculated by using the output energy, which is found using the temperature of the flue gas. Therefore this calculation is still the ratio of heat transferred to the room to the heat lost up the stack; it is just in a form that takes into account the entire test duration.

$$Heat\ Transfer\ efficiency = \frac{Overall\ efficiency}{Combustion\ efficiency} \quad (4)$$

To calculate the amount of particulates collected during each test run, the weights of the filter before and after the test run were determined a scale with a sensitivity of 0.1 mg. Particulates were also washed out of the silicon tubing with DI water, and the washes were collected and analyzed for particulates according to Method 5.[15]

To determine the total amount of particulates given off by the stove during each test, two ratios were calculated: the ratio of the flue gas flow rate in the stove pipe to the flue gas flow rate in the particulate line was calculated from experimental test data as shown in Equation (5),

$$Flow\ Ratio = \frac{Stovepipe\ flowrate}{Particulate\ train\ flowrate} \quad (5)$$

and the ratio of the particulates collected in the DI water to the particulates collected on the filter was calculated as shown in Equation (6).

$$Particualte\ Ratio = \frac{Particulates\ in\ DI\ water}{Particulates\ \ on\ filter} \tag{6}$$

This ratio was found to range from 3.1 to 3.6 with an average of 3.35. Therefore, the user can merely multiply the weight of the particulates collected on the filter by this ratio and obtain a precise estimate of the particulate emissions of the stove in question.

The results of the previously presented calculations for efficiency and PM emissions are represented cumulatively in Table 1 along with other pertinent information gathered during the test runs.

Table 1: Reduced Data From Experimental Testing

Test Run	**1**	**2**	**3**	**4**	**5**
Primary Air (% open)	>100	100	100	50	50
Test Load Weight (lb)	67.7	69.9	66.1	59.5	71.8
Test duration (h)	1.42	2.08	1.75	2.08	2.75
Input Energy (Btu)	498,265	514,456	486,489	437,913	528,440
Output Energy (Btu)	239,088	274,121	251,074	232,448	323,730
Overall Efficiency (%)	48	53.3	51.6	53.9	61.3
Combustion Efficiency (%)	91.9	91	94	85.5	90.9
Heat Transfer Efficiency (%)	52	59	55	62	67
Particulate (g/hr)	4.44	1.11	1.35	.752	.658
CO Emissions (g/hr)	2,150	1,643	1,275	1,995	1,285

Temperature of the flue gas above the stove and overall efficiency are visually represented with respect to a time fraction in Figure 5 and Figure 6, respectively. Time fraction is defined as the instantaneous time of the data point divided by the total run time of the individual test. Time fraction was calculated and used to plot the results because the total run times for each individual test varied between 85 minutes and 165 minutes.

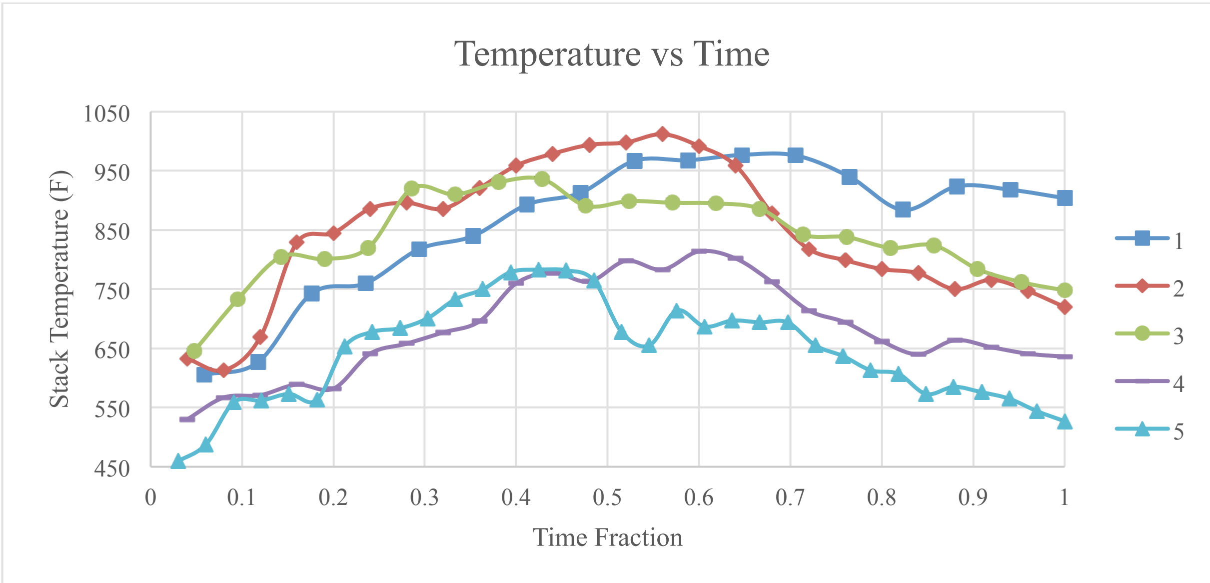

Figure 5: Temperature of Flue Gas 8 ft Above Scales Over Time Fraction During Testing Period

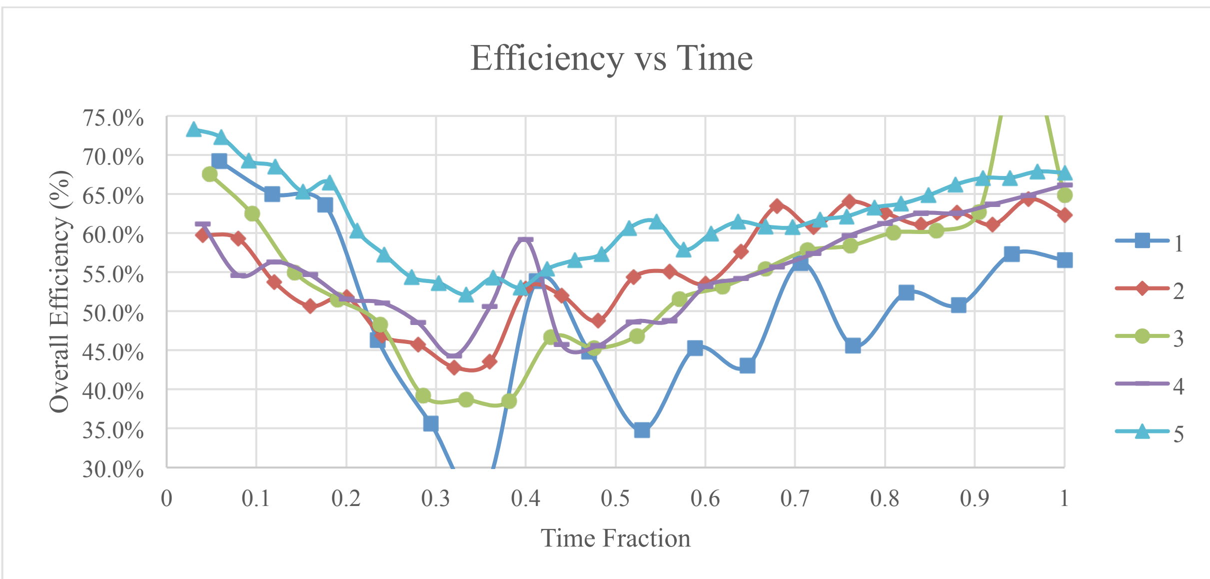

Figure 6: Instantaneous Overall Efficiency Over Time Fraction

Variability between Tests 1, 2, and 3 may be explained by a small modification made to the stove after Test 1. Test 1 was performed with five primary air inlets open in the stove. After Test 1 was completed, it was deemed prudent to operate the stove with only four primary air inlets open. This setup (four inlets) was then defined as the 100% primary air standard. Test 1 was effectively run with greater than 100% primary air, which caused a higher burn rate and a lower overall efficiency. It is likely that if Test 1 had been run at 100% primary air, then the results would have been closer to those of Tests 2 and 3. Variability between Tests 4 and 5 may be explained by a small malfunction with the testing apparatus that occurred just prior to data collection. The stovepipe installed on the outside of the facility was subjected to strong winds on the day of testing. The connections of the stovepipe were compromised and a large quantity of ambient air was able to enter the system. Dead time in the system caused CO and CO_2 readings to remain inaccurate for an extended period of time. Because the determination of efficiency is strongly dependent on the ratio of CO to CO_2, this mishap at the beginning of the test affected the average of the efficiency calculation. This effect can be seen in Figure X. It is also possible to see from Figure X that as the test drew to a close, Test 4 recovered and approached the same values obtained by Test 5.

The results from the PM emissions calculations were linearly consistent, but uncharacteristically low for the size of the stove and calculated efficiencies. This systematic error can be attributed to three separate causes: extremely high burn rates during test runs, an insufficient quantity of filter holders, and the location of the sampling port. First, abnormally high burn rates during test runs cause incredibly high temperatures, which in turn cause the PM to degrade as it moves through the stove pipe after it has been released from the fire itself. This additional PM degradation produces misleading data by yielding lower emissions on the filter than is actually produced by the burn. Second, an insufficient amount of filters allows PM to pass through the sampling train and be exhausted to the atmosphere without being collected in the filter or tubing, thus giving deceiving PM collection data. Third, the PM sampling port was placed further down the line, creating a longer path for the flue gas to traverse before being pulled into the train. This increased distance and residence time allows PM to accumulate on the stovepipe surfaces, thus reducing the measured emissions when the flue gas is eventually pulled into the sampling train.

Results from the volumetric bag collection method were analyzed to determine if the use of scales could be replaced by this significantly cheaper method. A method was used to determine the instantaneous burn rate in the stove, which is needed to give the current weight of wood in the stove for data reduction. Flow rate readings were recorded every ten minutes during three different tests. Percent difference between the actual weight loss given from the scales and the calculated weight loss at each recorded time was found and then averaged to determine how much error can be expected for each time period. Tests 1, 2, and 3 gave average percent differences of 75%, 86%, and 69% respectively. These large errors revealed that the volumetric collection device could not be used and that scales were needed to find the most accurate measurements for the CSA program.

The oxygen analyzer was used to be a redundant check on the stoichiometric calculated value of oxygen in the flue gas. Results from the recorded oxygen values were significantly different than the ones calculated in the CSA program. Recorded values ranged from 17-19% where the calculated values range from 0-14%. This is due to the fact the operating temperature for the oxygen analyzer was exceeded and the sample point that housed the electrode could not keep the air from entering during measurements, and these high temperatures compromised the electrode. The loss of this redundant measurement was unfortunate, but did not compromise the calculations.

Moving forward, six additional tests will be performed using an improved testing apparatus as set forth by the Optimal Apparatus section of this report. Three tests will be conducted at 100% primary air, and three tests will be conducted at 50% primary air. These tests should affirm the repeatability of results, while using a streamlined apparatus and simplified procedure. The time delay from the stovepipe to the analyzer due to the low flow rate of the sample stream will also be analyzed and included in these future tests to improve the calcualtions and results. To measure the accuracy of the Hog Method test for efficiency and PM emissions, it would be beneficial to obtain an EPA certified stove with known values for efficiency and PM emissions, and compare these numbers to the calculated results for the Hog Method. As it stands, the tested stove is far from passing EPA certification, and many more modifications and tests would be necessary to bring it within the required specifications.

OPTIMAL APPARATUS

The experimental design previously presented still contains a level of complexity that the StoveHogs believe may be eliminated by an even simpler testing apparatus. After much research, experimentation, and modifications to the initial design, the team has concluded that given more time and a more expansive budget, an even simpler and more accurate design could be achieved. The Optimal Hog Method (OHM) allows for construction and operation to proceed more smoothly, to take less time to complete, and to have a lower capital cost.

Eliminating the volumetric bag collection method allows for the outdoor heat exchanger and variable speed fan to be excluded. This operation allows the stove to create its own natural draft, and renders the manometer used for monitoring draft and the associated tests obsolete. There is no need for additional stovepipe on the outside wall of the facility.

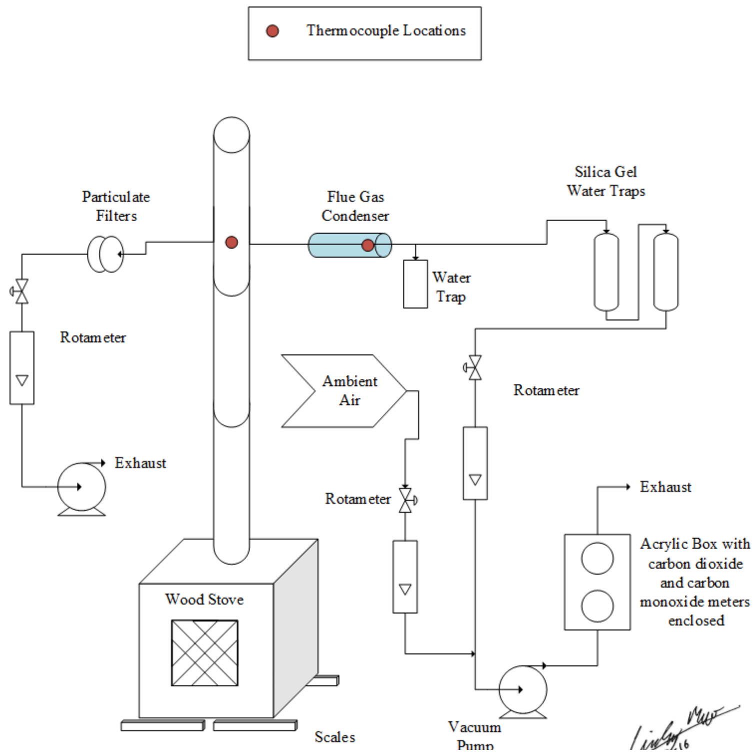

Figure 7: Optimal Design Apparatus

In the OHM, the efficiency sampling train and the PM emissions sampling train are kept as two separate sampling trains. Two steel bulkhead fittings should be placed in the stovepipe at 8 feet above the base of the stove, providing ports for each of the sampling trains describe in the Hog Method. The two sampling trains in the OHM will serve the same purposes as their counterparts in the Hog Method with slight changes. For the efficiency sampling train a condenser will be added before entering the silica gel beds. The shortest length of tubing possible should be used to reduce the time delay to the gas analyzers. Initially, the hot flue gas travels to a simple condenser constructed from an inverted two-liter bottle. The silicone tube is directed in through the opening cut in the bottom of the two-liter bottle and out through a hole drilled in the cap. The condenser is filled with water and should be kept lower than 50°F to ensure full condensation of the water in the flue gas. A tee with a vertical run is placed at the discharge of the cap. Cooling and condensing is necessary in the sample train to ensure that the sample taken is dry gas. Out of the condenser the flue gas will travel through a water trap to remove the majority of the condensed water. The water trap allows condensation to drain out of the line while directing the cooled flue gas to the silica gel beds. From the water trap onward, the OHM utilizes the efficiency train developed previously for the Hog Method. There are only two variations in the OHM from the design presented in the Hog Method for collecting PM. In the OHM two filters are used in series to ensure that all particulates are collected for measurement and results calculations. In the OHM acetone is then used to clean the lines to collect any oily residue caught in the lines. The schematic for the optimal design can be seen in Figure 7.

The dry gas analyzers are arguably the most important component of the sampling train for the OHM. They also serve as a limiting factor in the OHM design. Each analyzer must have the ability to take continuous readings. The price of the analyzer is directly related to the capabilities of the analyzer – the higher the price tag, the more accurate and reliable the readings will be.

The stove operation of the OHM is identical to that of the Hog Method. The pre-test and test charges are created and used in the same fashion. During the test run, scale, rotameter, and composition meter readings are to be collected at five-minute intervals. The user should be conscious of maintaining the ratio of flue gas to dilution air during the entire test as these values may fluctuate as the pump reaches equilibrium.

ECONOMIC ANALYSES

When compiling these cost estimates it was assumed that the consumer or hired personnel possess power tools for construction, wood for burning, power sources and extension cords for equipment operation, and tables or supports for the constructed apparatus. As compared to the cost of installing a complete test apparatus at a full-scale facility, which can cost up to $90,000, the overall cost of assembling and using either of these methods represents a cost savings of approximately 97%.[13]

Table 2: Cost Estimate Comparison

Cost Category	Experimental Apparatus Cost	Optimal Apparatus Cost
Stove Pipe and Fittings	$316	$80
Heat Exchanger System	$875	$0
Efficiency Train	$692	$670
Particulate Train	$468	$611
Burn Rate Determination	$517	$253
General/Safety Equipment	$110	$110
Shipping	$400	$350
Total	**$3098**	**$2044**

Experimental Apparatus

The cost estimate for the experimental test method was compiled in two separate general categories: equipment and shipping costs. The shipping cost was estimated upon the US Postal Service shipping all of the required equipment to the consumer a distance of 500 miles. The final values for these costs are listed in Table 2. The main contributors to these totals were the duct fan and water pump, which were over $250 each and the carbon dioxide and carbon monoxide meters, which were both over $120.

Optimal Method

As an alternative to the experimental apparatus, several simplifications were made to reduce the cost and increase the functionality of the testing apparatus. These improvements reduced the amount of equipment and overall weight that must be shipped by eliminating the need for several expensive and heavy pieces of equipment. As seen above, the overall cost was reduced by $1336, about 43% of the cost of the full experimental design. The greatest cost reduction from the experimental design came from the heat exchanger system. This is due to the fact that this entire system was rendered obsolete by the simplifications made in the optimal design. As shown in the table, the particulate train cost increased by $113 from the cost for the experimental design. This rise was due to the addition of a second filter holder to ensure that no particulates were blown through the primary filter in the experimental design.

IMPLEMENTATION

Both of the sampling trains the Optimal Hog Method apparatus may have significant importance in the design of a wood stove for commercial sale as a residential heating unit, but they also have the potential to be useful beyond this niche market. Approximately 70% of households in the United States use some type of combustion for residential heating.[22] This percentage includes units that burn natural gas, fuel oil, coal, and biomass, and the Hog Method could be applied to all type of units. The wide spread applicability of the Hog Method would benefit many small businesses, hopeful startup companies, and backyard inventors focused on producing combustion units for residential heating. Not only would the Hog Method provide producers of heating units the ability to test efficiencies, it would also provide a simple way for the conscientious wood-burning individual to assess the necessity for any modifications to an older, in-use stove to fully harness the heating benefits of their unit. These units may be primarily wood burning stoves, but the method could easily be applied to residential heaters such as boilers and furnaces (which may run on wood or other fuel sources) to determine the efficiency of the combustion occurring. The environmental and social benefit of marketing the Hog Method to consumers burning in older, un-certified stoves has the potential to be immense. Approximately 11% of harmful, cancer causing particulates in the atmosphere come directly from the combustion of wood, and approximately 2.4 million Americans rely on burning wood as a primary source of heating.[18,22] Introducing a method that would enable wood burning households to improve how they burn their stoves has the potential to reduce the amount of harmful particulates in the air. The Hog Method has the potential to provide this benefit, which holistically addresses the health and environmental concerns of the EPA, while also providing an economic benefit on multiple levels.

The Hog Method can reduce the financial burden that introducing a new design for testing creates on manufacturers. Research and development costs for wood stove manufacturers have increased substantially with the implementation of EPA regulations. The EPA estimates that the newest regulations, which dictate a maximum PM emissions limit of 2.5 g/hr, will cumulatively cost manufacturers approximately $45.7 million.[18] The increase in cost has already driven many small stove manufacturers out of the market and contributed to a great consolidation of manufacturers. Since the EPA began requiring certification in 1988, there has been just under a 90% decline in the number of facilities producing wood stoves.[6] By lowering the overall cost, the Hog Method may have the potential to re-expand and re-open the wood burning stove market to smaller competitors. Provided with drawings, equipment specifications, building instructions, and operating instructions, interested individuals could assemble the apparatus to be in-shop and use it time and again to assess the performance of a stove before sending larger sums of money to research facilities for similar testing.

The economic benefit then is two-fold: (1) capital investment; because the Hog Method may reduce the sharp rise in economic investment manufacturers will have to make in their stoves to develop them into EPA certifiable products, consumers will continue to be able to purchase new, efficient stoves for a reasonable price, and (2) run cost; whether the consumer buys a new, efficient stove for the lower price as stated previously, or is interested in improving the efficiency of an old stove, the increased efficiency of the stoves means a lower fuel cost for the consumers. The Hog Method, if properly marketed and constructed, has the potential to reshape the stove industry while striving to achieve the EPA's goals and keeping wood burning an affordable and safe method of residential heating.

CONSIDERATIONS

This apparatus is designed to provide preliminary test results, and cannot guarantee a positive result when the stove is submitted for EPA certification tests. The design presented in this report is intended for use by a variety of consumers, including persons who would be interested in constructing and operating the apparatus with no professional input. While this section strives to address all potential health and safety concerns, it is intelligent to obtain all Safety Data Sheets (SDS) and material from the Occupational Safety and Health Administration (OSHA) about a working environment if any questions about personal safety arise.

Concrete fiberboard was used during the construction of the heat exchanger enclosure. Cutting and drilling concrete fiberboard may release harmful crystalline silica particulates into the working-environment air, which may cause damage to the lungs and respiratory system. It is considered best practice to complete any cutting or drilling through concrete fiberboard in a well-ventilated area, and to always wear a ventilator to avoid inhaling large quantities of particulates. While the Hog Method stove testing does not introduce any additional material in the atmosphere outside of the emissions inherent to burning fuel, the location of the flue gas vent is another important personal safety consideration. Particulates in the flue gas are irritating to the eyes and lungs if inhaled. If the apparatus installation allows for operation at waist or ground level, it is prudent to allow the gas to vent away from areas where personnel will be operating, or well above head height. Personnel should wear appropriate gloves and long sleeves at all times while operating around the stove due to the presence of hot surfaces. Applications of the design may require parts to be installed well above head height both inside and outside of the testing facility. Ladders or scaffolding will be necessary to complete the installation and must be properly stabilized on a level base before operating personnel ascend. Falls are among the leading causes of serious injuries related to work, and best practices provided by OSHA are a good resource for protecting personnel on the job.[17] There are multiple pieces of heavy equipment associated with the testing. Proper lifting technique should be observed when moving heavy objects manually.[19] Again, OSHA is an appropriate resource for information on heavy lifting practices and all other safe work practices.[19]

CONCLUSIONS

Alongside many industry leaders, the EPA has attempted to standardize the process of evaluating wood stoves to the greatest extent possible by providing a standard by which stoves can be compared to one another. Though this effort is valiant and important to controlling air quality, the stricter guidelines are putting extreme pressures on small manufacturers. Though larger manufacturers are able to stomach the rising cost, consumers are feeling the effect. Moving from 4.5g/hr of PM emissions to 2 g/hr is a significant change that has created a demand for incredible amounts of research to be done[6,11]. An industry giant recently invested over $150,000 into a non-catalytic stove to bring it down to the EPA's 2020 requirement of 2 g/hr. In order to find success, they were forced to convert the unit into a catalytic stove – a more expensive alternative for consumers to consider. The newly certified stove will potentially retail at or above $4,000 – a considerable capital investment for a middle- or low-income family. As a result of this hike in certification costs associated with the R&D required to achieve recertification in 2020, the prices of wood stoves are again on the rise. The overarching result is that a traditionally reliable and cheap method of residential heating may no longer be a viable option for the portion of the population who has traditionally relied on wood as a cheaper alternative for residential heating.

This hike in market prices due to stricter requirements by the EPA has resulted in many unintended consequences, including a rise in uncertified wood stove sales through unregulated sites, a consumer shift to buying coal fired stoves, and a desire to build custom stoves which go untested in any way. The stricter the regulations become, the more difficult it becomes for small business to participate in the industry. The steady decline in number of wood stove manufacturers is directly related to the increased difficulty of meeting more stringent standards. The need for a method that can decrease the immediate economic burden on stove manufacturers is important in order to keep wood stoves as an economically viable, sustainable heating option. While larger manufacturers may be able to absorb the cost more effectively and keep their prices steady, smaller manufacturers will be forced to raise their prices or sell-out to a larger company. The Hog Method addresses these unintended consequences by providing a way for interested parties to gather data on a wood-burning unit and ready it for certification at a significantly lower price tag than options that are currently available.

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WERC REPORT AUDITS

Task 1

EPA Testing of Wood Burning Stoves

Department of Chemical Engineering
University of Arkansas
Fayetteville, AR

The following audits of the StoveHogs' project and report were completed by John Ackerly (compiled by Gabriella McConnel) of The Alliance for Green Heat, Ben Myren of Myren Consulting, Inc., and John Steinert of Dirigo Labs. They are presented here in their original and unadulterated forms, and in the order in which they were returned to the team. Areas of the StoveHogs' report were revisited and modified in response to comments presented here. Special thanks to Ben Myren for hosting a student-member of the StoveHogs team at his Colville, WA lab site, and working to get students' access at the HPBExpo in New Orleans, LA. This project was benefitted immensely by his experience, knowledge and advice.

In addition to thanking the reviewers of this report for the time and energy associated with completing these audits, the StoveHogs would like to acknowledge others who were important to the completion of the project. Owner and Operator of RCW Welding and Design Mr. Roger Watkins for allowing the team space in his shop for the testing. Designer and stove aficionado Mr. Jim Donnohue for making sure the team had all the necessary supplies in Huntsville, AR. Shop director Mr. George Fordyce for his ability to build all the things the team needed on campus. Equipment manager and organizer Mr. Harold Watkins for allowing the team to take testing equipment all the way to Huntsville, AR. Dr. Greg Thoma for providing insight and direction for the written report. And Advisors Dr. Penney and Dr. Ackerson for demanding quality deliverables.

John Ackerly – Alliance for Green Heat

Alliance for Green Heat
512 Elm Ave.
Takoma Park, MD 20912

March 14, 2016

Team StoveHogs
Department of Chemical Engineering
University of Arkansas
Fayetteville, AR 20912

Attention: Teni Butler, Team StoveHogs

I have reviewed your report, Efficiency and Particulate Matter Emissions Testing of Wood Burning Heating units, and I am thoroughly impressed. I have been in the biomass thermal industry for quite some time, and had no idea that your team would be able to get such a grasp on the technical side or the regulatory issues. The writing is very clear and organized, so I have only included specific comments for correction and did not mention the numerous great sections.

I did not include comments on the test method, as I think someone with a more technical background might answer those best. However, I think you may want to mention using the option of a Testo for pre-certification testing. For $2,000, you can have an instrument that gives you real-time, digital numbers. We have been very surprised how many inventors spend years in development without any instrumentation, so they don't really know if a design change is making the stove cleaner or more efficient, or the opposite.

I have listed my comments and suggestions below. The page numbers I listed below correspond to the PDF document, not the numbers listed at the bottom of the page.

I. (p. 4) The cost of heating with electricity is much more of an issue than access to electricity

II. (p. 5) Particulate Matter certification can be lower than the 10K to 12K range, but certification for safety usually drives up the cost to this amount.
   - Research and development costs are really dependent on the situation. Done out of house, 100-150K is a good estimate. However, it is harder to put a dollar figure on small players, as their time is not valued at professional rates ($50-$150/hr). In addition, a lot of R&D is done using employees that earn $20-$30/hr, greatly reducing the cost when compared to out of house R&D.
   - Another way for innovation to enter the market is by a backyard inventor selling his or her idea to an established and experienced stove maker. Stove manufacturers are notorious for using each other's ideas, just like any other industry, so innovation tends to spread.
   - One of the biggest reasons stoves don't get cleaner and more efficient is because they aren't forced to. Efficiency is completely voluntary, and there is no minimum value to meet as there is a maximum value with PM. However, both of these parameters are relatively cheap and easy to test for in the R&D phase (using a Testo 320).

III. (p. 6) In order to increase efficiency, O_2 in the stack must be lowered, not CO.
   - Efficiency and cleanliness do not correlate very well. I theory they should and even sometimes do correlate, but often they just don't. High combustion efficiency is beneficial for cleanliness, but thermal, or overall efficiency has much more to do with heat exchanger performance.
   - Geothermal (real niche market), Wood (large appeal), Solar PV (was a niche market for a long time but has developed a larger appeal, but still has a long way to go to catch up with stove installations)
   - By using maximum air and 50% air, two of the easier burn rates are being selected. It is the lowest air setting that the majority struggle with.

IV. (p. 23) In response to: "The increase in cost has already driven many stove manufacturers out of the market."

- The 1988 regulations drove hundreds out of business, but the 2015 ones hardly drove any stove manufactures out. It did drive a bunch of small boiler manufacturers out of business. Also, it's hard to pin consolidation on the NSPS alone.

V. (p. 25) In response to: "Though this effort is valiant and important to controlling air quality, the stricter guidelines are putting extreme pressures on small manufacturers."

- Bigger companies are the ones driving the litigation against the EPA. I can't say that it is hitting smaller companies that much harder – it all depends on internal R&D capacity and culture. Companies with a relaxed culture, less concerned with aesthetics and more with profit, are struggling the most.
- In response to: "The overarching result is that a traditionally reliable and cheap method of residential heating may no longer be a viable option for the portion of the population who has traditionally relied on wood as a cheaper alternative for residential heating."
    i. I don't think this is true, given the plethora of Englander and other stoves that sell for less than $1,500. We just an HHT pellet stove for $1,200 and its .3 grams an hour – one of the very cleanest and has good efficiency. Modern mass construction methods are greatly reducing the price.
- In response to: "This hike in market prices due to stricter requirements by the EPA has resulted in many unintended consequences, including a rise in uncertified wood stove sales through unregulated sites, a consumer shift to buying coal fired stoves, and a desire to build custom stoves which go untested in any way."
    i. Some of this may be true, but I haven't seen much data to support it. A lot of it is conjecture from industry trying to make the case against regulations. More and more stoves on the secondhand market are EPA certified stoves. However, when you can buy a new EPA certified wood stove for $650, why even buy a used one.
- Coal stove sales are not tracked, as far as I know, and dealers report some new customers, but also some still switching to wood or pellets (very regional).

VI. (p.26) I am not convinced that the prices of wood stoves are on the rise. More consumers may be buying value brands – like Englander – which could lower the volume of sales by more expensive brands (impacting prices and profits).

- There is also not a clear relationship between efficiency, PM, and price. Some of cheapest stoves are some of the cleanest and/or most efficient. We don't know if this is because a lab somehow coaxed an unreasonable low PM number during the certification test or not, in some cases. Cheaper stoves may be lighter stoves, using less steel, but then again, there is not always a correlation between weight and price.

VII. (p. 28) In response to: "Research and development costs for wood stove manufacturers have increased substantially with the implementation of EPA regulations."

- The NSPS at 4.5 grams an hour is the status quo. Very few stoves were above 4.5 gr/hr. From manufacturers I talk to, their costs to certify prior to May 15, 2015 and after are about the same. Meeting the 2020 standards will cost a laggard company more, but companies with good internal R & D are already meeting the 2.0 gram an hour.

As a whole, I thought the piece was concise, clear, and well researched. I look forward to seeing the results of the competition and wish your team good luck. I look forward to publicizing this and please let me know when I am able to do so.

Kind Regards,

John Ackerly
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March 15, 2016

WERC 2016
Efficiency and Particulate Matter
Emissions Testing of Wood Burning
Heating Units – Task #1
Stove Hogs
Dept of Chemical Engineering
University of Arkansas
Fayetteville, AR

My name is John Steinert and I am the President of Dirigo Laboratories, Inc. I have been asked to review the Stove Hogs Teams paper on the "Efficiency and Particulate Matter Emissions Testing of Wood Burning Heating Units". Dirigo Laboratories is an EPA accredited test lab that specializes in the emissions testing of residential wood fired heating appliances. Dirigo also holds the following ISO accreditations - ISO 17020, 17025, and 17065.

After reviewing your report, it is clear to me that the team quickly realized the complexity of the world of stove testing. The current EPA and associated test methods are time consuming, expensive and complex. The development of a more economical and real world method is something that is worth pursuing. The Hog Method is a step in the right direction.

Because of the large firebox of the stove that was being tested it is difficult to compare with more traditionally sized stoves. The low particulate emissions indicate that these numbers are not consistent with a stove of this size. There would need to be quite a bit of additional testing to determine the reasons behind the discrepancy. I would have liked to seen additional test runs using the Hog Method to better form an opinion of the results.

A couple of comments:

- The moisture of the wood used for testing was 14% - was this dry or wet basis? Either way, this was very dry wood to use for this testing. The current EPA test methods use a range of 18%-25% Dry-Basis. The dry wood could have contributed to the over firing of the unit in the higher burn rate categories

- I would agree that the OHM could provide for a simpler and user friendly design but realize that the time constraints would not allow for it. In order to prove the method out and get to where it could be repeatable could take months if not years.

The OHM method is promising and has potential to keep costs down for smaller manufacturers that are trying to develop new product. More time would be needed to develop the method and work out the bugs that were identified in the report. That being said, the methodology is sound and is worth pursuing.

Overall, the paper was well thought out and clearly stated the challenges that are involved in stove testing. I was impressed with the team's ability to adapt to the challenges that it faced and adjust accordingly.

Please feel free to contact me I can be of additional help.

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RE: Audit, Review and Comment on the Wood Hawg's Proposed Low Cost Measurement Method for Determining PM and CO Emissions from Wood Burning Appliances

Someone once told me that when a wood fire is burning, there are 35,000 chemical reactions taking place every second. After 30 plus years of testing appliances that burn solid biomass fuels, I can say that I think that number may be low. Thus, any method used to measure the PM and CO emissions from a wood fire has to be a very robust system because of the wild variations that can occur at any time when a fire is burning, e.g., a log can roll, which changes the air flow, which changes the organic release rate, which changes the combustion taking place, which in turn changes the PM and CO emissions. Thus as a person who has been testing wood burning appliances, one of the first things I looked for in the HAWG method was whether or not I thought it was a robust enough system that could handle the wide variation in PM and CO emissions that can occur, especially early on in the new product development process. In my opinion I think the HAWG method is robust enough to do that.

In these past 30 years, I have also participated in the development of several different test methods used to determine the PM and CO emissions from several different solid fuel appliance categories, the most recent being a cord wood operating and fueling protocol for wood stoves. This test method has been under development for over 3 years now and we still have a ways to go to get it "right". I say this because I am certain that the HAWG method will, in all likelihood, have to undergo a number of substantial revisions before it works reliably. But that is to be expected. In fact, ASTM standards are required to be reviewed every 5 years to insure that the ASTM standards are based upon the best available information and data.

One of the things that I think will need to be changed is the 12 foot stack height. A one story house will typically have a 14-16 foot chimney. Certainly 12 feet will work, but since the chimney height affects the amount of static pressure (draft) a chimney generates, the short 12 foot chimney will not generate the same draft as a 15 foot chimney and since that draft is the "engine" that makes a wood stove work, this reduced draft will affect the air flow through the unit which in turn will affect the combustion taking place which in turn will affect both PM and CO emissions. If this is not corrected it could lead to a situation where the difference in chimney heights could skew the test results. Since EPA certification tests are always conducted with a 14-16 foot chimney, that difference could create significant problems for the person using the HAWG method.

The point here is that what the HAWGS have developed works and with refinement would certainly meet the stated project objective: develop a low cost test method that can be used as a reliable predictor of PM and CO emissions that can be used by inventors and others interested in developing new clean burning appliances that burn wood. Here I think I need to put "low cost" in perspective. The equipment required to run an EPA wood stove certification test can easily cost upwards of $250,000.00 with an individual test run costing $2000.00 or more. Assembling the equipment required in the HAWG method and running a test would not come even close to that amount. So again, what has been developed meets the stated project goal of "low cost".

It has definitely been a pleasure and very interesting to work with the HAWGS. They tackled a very difficult testing issue and came away with a method that has a reasonable chance of being viable. Certainly one of the (unstated) goals of a project like this is to require each individual involved to really "stretch" to put all of the required pieces together in a way that works successfully. And that they did.

If anyone has any questions about my comments, fell free to contact me anytime.

Regards,

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